AD-A262 820

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

AGENC[Y USE ONLY]	14 Feb 92	3. REPORT TYPE AND DATES COVERED: Final 01 Aug 85 to 31 Jul 91

TITLE AND SUBTITLE
Sensor Array Processing

5. FUNDING NUMBERS
N00014-85-K-0550

AUTHOR(S)
Thomas Kailath

PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Information Systems Laboratory
Dept. of Electrical Engineering
Stanford University
Stanford, CA 94305-4055

8. PERFORMING ORGANIZATION REPORT NUMBER
1

SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Naval Research
800 N. Quincy St., BCT No. 1
Arlington, VA 22217-5660

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
1

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unlimited

DISTRIBUTION STATEMENT A
Approved for public release;
Distribution Unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Research issues specifically related to the processing of data produced by arrays of sensors as might be encountered in various remote sensing scenarios and direction finding problems.

REPRODUCED BY
U.S. DEPARTMENT OF COMMERCE
NATIONAL TECHNICAL
INFORMATION SERVICE
SPRINGFIELD, VA 22161

93-07371

14. SUBJECT TERMS
Sensor array data processing Direction finding

15. NUMBER OF PAGES
12

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL

DEPARTMENT OF ELECTRICAL ENGINEERING
STANFORD UNIVERSITY, STANFORD, CALIFORNIA 94305-4055

THOMAS KAILATH
HITACHI AMERICA PROFESSOR OF ENGINEERING

February 14, 1992

Dr. R. Madan
Code 1114
Office of Naval Research
800 North Quincy Street
Arlington, VA 22217-5000

re: N00014-85-K-0550

Dear Dr. Madan:

On behalf of Professor T. Kailath, I am enclosing the final report on the above referenced contract.

Sincerely yours,

Barbara McKee
Administrative Assistant

bMcK

cc: P. McCabe
P. Biddle

encl: 1

PHONE: 415-723-3688 TELEX: 348402 stanfrd stnu FAX: 415-723-8473 EMAIL: tk@isl.stanford.edu OFFICE: Durand 117

Sensor Array Processing

Office of Naval Research Contract N00014-85-K-0550, Task NR-SDRB-002

Final Technical Report for the Period August 1, 1985 to July 31, 1991

Thomas Kailath
Information Systems Laboratory
Department of Electrical Engineering
Stanford University
Stanford, CA 94305

1 Introduction

This document is the final technical report for the Office of Naval Research's contract N00014–85–K–0550, *Sensor Array Processing*. The contract was initially granted for the period July 1, 1985 through June 30, 1988, and subsequently extended to the period August 1, 1988 through July 31, 1991. The proposals submitted for these two contract periods described research issues specifically related to the processing of data produced by arrays of sensors as might be encountered in various remote sensing scenarios and direction finding problems. We believe that our research efforts in these regards have produced significant results. Moreover, we successfully applied the understanding gained from our study of sensor arrays to other related problems including time series analysis and state-space system identification. In addition, we have developed new and computationally efficient numerical analysis procedures that render the sensor array processing algorithms developed under this contract and elsewhere practical for "real-time" implementation.

The remainder of this document is organized as follows. Section 2 provides an outline of the research results obtained during the contract period. For each related group of results, pointers to the various technical reports containing detailed descriptions of these results are provided. Section 3 lists the technical reports submitted earlier during the contract period, along with the indexing keys used in Section 2. The final section, Section 4, tabulates our publications on research related to this contract.

2 Research Results

Narrowband Sensor Array Processing Algorithms

The model for the so-called *narrowband* sensor array processing problem is given by equation (1). Its apparent simplicity belies its mathematical complexity and its applicability to a rich collection of engineering applications. The model applies, for instance, to the case where signal propagation times across an array are small compared to their bandwidth which is the origin of the term *narrowband*.

$$x(t) = A(\Theta)s(t,\Theta) + n(t) \tag{1}$$

Θ represents the parameters to be estimated (*e.g.* directions of arrival) and $s(t,\Theta)$ is the d dimensional vector of source signals. $A(\Theta)$ is an $m \times d$ dimensional array mapping the source signals s into m sensor outputs, and $n(t)$ represents additive sensor noise. This same model can be used for time series analysis (the concept of sensors is replaced by delay-line taps) where the goal is to estimate the number

and frequencies of sinusoids in noise, as well for system identification problems in which one has input and output data for a certain system and wishes to estimate a state-space model. Our group's research in this area concentrated upon the class of subspace algorithms, the progenitor of which was Ralph Schmidt's MUSIC algorithm (also developed at Stanford).

In the area of algorithm development, our goals were the development of algorithms that were more efficient than existing algorithms and the unification of existing algorithms in a common framework. A key result was the development of ESPRIT (Estimation of Signal Parameters via Rotational Invariance Techniques). ESPRIT is distinguished by the fact that it does not require *a priori* knowledge of $A(\Theta)$ nor does it involve a search in parameter space. These two requirements are obviated by assuming a shift invariance structure that is present in many sensor arrangements (*e.g.* uniform linear arrays, tapped delay lines, cross arrays). Additional invariances present in the spatial (temporal) distribution of the sensors can be exploited by the MI-ESPRIT algorithm (Multiple Invariance) to improve parameter estimates. The references for ESPRIT are I, J and L.

Another key development was the SSF (Subspace Fitting) framework and its associated algorithm WSF (Weighted Subspace Fitting). SSF provides a single unifying framework that subsumes most of the subspace-based estimation techniques, including MUSIC, MD-MUSIC, Root-MUSIC, ESPRIT, beamforming and deterministic ML (maximum likelihood). Its associated algorithm, WSF, is asymptotically efficient (*i.e.* it achieves the Cramér-Rao bound) for the stochastic ML formulation of the array processing problem at a fraction of the cost associated with a direct minimization of the ML cost function. The references for SSF and WSF are J, K and L.

Statistical Analysis of Narrowband Algorithms

The unifying framework of SSF has proven effective in the asymptotic statistical analysis of subspace-based techniques which it subsumes. Performance analyses have been performed for ESPRIT, stochastic ML, MUSIC and MD-MUSIC. The appropriate references are J, K and L.

Sensitivity Analysis of Narrowband Algorithms

Closely related to the statistical analysis of various subspace-based algorithms, is the analysis of these algorithms' sensitivities to modelling errors. The spacing of elements in a "uniform linear array" might not be exactly constant, for instance, or the gain and phase characteristics of the sensors might not be exactly known. The effect of these modelling errors on the algorithms' performance can be characterized using the SSF framework. The appropriate reference is L.

Time Series Analysis

Many researchers have noted that the problem of identifying directions of arrival

with a uniformly linear array is nearly identical to that of identifying the frequencies of sinusoids in a uniformly sampled time series. The key difference is that in the former case many data records, or "snapshots", are obtained while in the latter a single data record is obtained. In the time series case, one typically forms a matrix of ersatz snapshots from the single data record before applying a subspace technique for the purpose of frequency estimation. We obtained results establishing the conditions under which this procedure will result in the desired estimates. the appropriate reference is L.

Signal Estimation

It is often desirable to obtain more information than just the directions of arrival in a sensor array processing scenario or the sinusoid frequencies in the case of time series analysis. One might want estimates of the individual signals in the array processing case (so-called *signal copy*). This difficulty of this problem is exacerbated when the source signals are correlated. Methods for estimating the source coherency structure and for estimating signals in the case of correlated sources are described in reference I. Similar problems arise in time series analysis when the sinusoids are phase-coupled — our results in this area are described in references J and K.

State-Space System Identification

Although linear state space models have become increasingly important in estimation and control since the pioneering work of Kalman, they have not been widely used in identification. One of the goals of our research has been to demonstrate that there are some important advantages in explicitly considering general state space forms in identification. The methods we studied exploit a certain shift structure in the input/output model for the data. The motivation for these new algorithms comes from some interesting connections linking the state space identification problem with sensor array signal processing. In particular, we have shown how the identification problem can be cast in the SSF framework. Of special interest is the fact that the dominant subspace can be weighted to emphasize certain directions in the so-called "signal" subspace where the signal-to-noise ratio is high. It has been demonstrated that for the identification problem, the ability to properly weight this subspace provides our algorithm with superior performance in cases involving nearly unobservable systems or an insufficiently exciting input sequence. The appropriate reference is M.

Numerical Analysis Results

A step common to all subspace algorithms is the estimation of the so-called "signal subspace". Classically, this is obtained via an eigendecomposition of the estimated measurement covariance matrix, requiring $O(m^3)$ operations. This op-

eration often dominates the computational requirements of a subspace algorithm and often renders real-time implementations infeasible. The FSD (Fast Subspace Decomposition), developed under this contract, obtains the signal subspace in $O(m^2 d)$ steps. In time series analysis problems, for example, m can be on the order of 100 (typically, $d \ll m$) and the computational savings afforded by FSD are manifest. The appropriate reference is M.

Wideband Sensor Array Processing Algorithms

When signal propagation times across an array are not small compared to their bandwidths, the model of equation (1) no longer applies. A number of approaches are possible in this case; we investigated two in particular. Using a wideband subspace model developed by Su and Morf, we investigated a wideband extension of the ESPRIT algorithm. Sensor outputs are preprocessed in the time domain to identify the poles of the emitter signals and ESPRIT is subsequently applied at the identified poles. ESPRIT is particularly well suited to this problem as knowledge of the array response (as a function of frequency as well as, say, angle) is not required. This work is reported in I, J and K.

Alternatively, one can exploit structural features of the emitter signals in the wideband case. Many digital communication signals (*e.g.* BPSK, QPSK, FSK) exhibit cyclostationarity. This property can be used to advantage in the wideband scenario and also for the purpose of reducing co-channel interference. The appropriate references are L and M.

The issue of adaptive beamforming for wideband systems was also addressed. The typical structure employed for this purpose is a bank of parallel tapped delay lines with adaptive weights at the output of each sensor. We developed a fast and numerically stable multichannel RLS (Recursive Least Squares) algorithm based on an underlying transversal filter architecture. These results are significant not only because they provides a fast algorithm for RLS, but because they debunked the widely held notion that stable transversal filter RLS implementations were impossible. This work is discussed in reference I.

Nearfield Sensor Array Processing

In both the narrow and wideband situations described above, it is assumed that the emitters are in the array's far-field so that the emitter wavefronts may be modelled as plane waves at the array. When the emitters are in the array's near-field, the curvature of the emitter wavefronts must be taken into account. Using a Fresnel approximation for the wavefronts, an algorithm employing the Wigner-Ville Distribution of the sensor outputs and ESPRIT was developed that generated

range and bearing estimates for the emitters. A discussion of this algorithm and Cramér-Rao bound comparisons is provided in reference I.

3 Technical Reports

The following table lists the various technical reports submitted in accordance with the contract. The column labeled "Key" is the indexing key used in Section 2 to refer a particular report. The interim technical report of July, 1988, I, subsumes the reports predating it and is therefore referred to in Section 2 to their exclusion.

Key	Date	Type	Title
A	Jan, 1986	Semi-Annual	*Sensor Array Processing*
B	Jun, 1986	Semi-Annual	*Sensor Array Processing*
C	Jul, 1986	Annual	*Sensor Array Processing*
D	Jan, 1987	Semi-Annual	*Sensor Array Processing*
E	May, 1987	Semi-Annual	*Sensor Array Processing*
F	Aug, 1987	Annual	*Sensor Array Processing*
G	Oct, 1987	Progress	*Wideband Direction of Arrival Techniques*
H	Dec, 1987	Semi-Annual	*Sensor Array Processing*
I	Jul, 1988	Interim	*Recent Advances in Sensor Array Processing*
J	Jan, 1989	Semi-Annual	*Sensor Array Processing*
K	Jul, 1989	Annual	*Sensor Array Processing*
L	Jan, 1990	Semi-Annual	*Sensor Array Processing*
M	Jul, 1990	Semi-Annual	*Sensor Array Processing*

4 Publications

Papers Published in Refereed Journals.

[1] A. Paulraj and T. Kailath, Eigenstructure Methods for Direction of Arrival Estimation in the Presence of Unknown Noise Fields, *IEEE Trans. ASSP*, Vol. ASSP-34, no. 1, pp. 13-20, February 1986.

[2] R. Roy, A. Paulraj and T. Kailath, ESPRIT – A Subspace Rotation Approach to Estimation of Parameters of Cisoids in Noise, *IEEE Trans. ASSP*, Vol. ASSP-34, no. 5, pp. 1340-1342, October 1986.

[3] A. Paulraj, R. Roy and T. Kailath, A Subspace Rotation Approach to Signal Parameter Estimation, Proc. IEEE, Vol. 74, no. 7, pp.1044-1046, July 1986.

[4] T. J. Shan, A. Paulraj and T. Kailath, On Smoothed Rank Profile Tests in Eigenstructure Methods for Directions-of-Arrival Estimation. *IEEE Trans. ASSP*, Vol. ASSP-35, no. 10, pp. 1377-1385, October 1987.

[5] A. Paulraj, V. U. Reddy, and T. Kailath, Analysis of signal cancellation due to multipath in optimum beamformers for moving arrays,, *IEEE Trans. Ocean Engrg.*, **OE-12**(1):163–172, January 1987.

[6] D. Spielman, A. Paulraj, and T. Kailath, Eigenstructure approach to directions-of-arrival estimation in ir detector arrays, *J. Appl. Optics*, **26**(2):199–202, January 1987.

[7] V. U. Reddy, A. Paulraj, and T. Kailath, Performance analysis of the optimum beamformer in the presence of correlated sources and its behavior under spatial smoothing, *IEEE Trans. Acoust. Speech Signal Process.*, **ASSP-35**(7):927–936, July 1987.

[8] R. Roy, A. Paulraj, and T. Kailath, ESPRIT - Estimation of Signal Parameters via Rotational Invariance Techniques, In E. F. Deprettere, editor, *Singular Value Decomposition and Signal Processing*, France, September 1987. Proc. Inter'l. Workshop on SVD and Signal Processing, Elsevier Science Publishers.

[9] T. J. Shan, A. Paulraj, and T. Kailath, On smoothed rank profile tests in eigenstructure approach to directions-of-arrival estimation, *IEEE Trans. Acoust. Speech Signal Process.*, **ASSP-35**(10):1377–1385, October 1987.

[10] Y. Bresler, V. U. Reddy, and T. Kailath, Optimum Beamforming for Coherent Signal and Interferences, *IEEE Trans. ASSP*, Vol. 36, no. 6, June 1988.

[11] Y. Bresler and T. Kailath, Model Based Tracking of Signal Shift and Shape, *Automatic Control and Production System*, special issue on Modeling-Identification Techniques in Signal Processing, no. 22, pp. 269-291, 1988.

[12] D. T. Slock and T. Kailath, A fast RLS transversal filter for adaptive linear phase filtering, *Internat. J. Adaptive Control and Signal Process.*, **2**:157–179, 1988.

[13] A. Paulraj and T. Kailath, Direction of arrival estimation by eigenstructure methods with imperfect spatial coherence of wavefronts,, *J. Acoust. Soc. of America*, **83**(3):1034–1040, March 1988.

[14] Y. Bresler, V. U. Reddy, and T. Kailath, Optimum beamforming for coherent signal and interferences,, *IEEE Trans. Acoust. Speech Signal Process.*, **36**(6):833–843, June 1988.

[15] Y. Yoganadam, V. U. Reddy, and T. Kailath, Performance analysis of the adaptive line enhancer for sinusoidal signals in broadband noise, *IEEE Trans. Acoust. Speech Signal Process.*, **36**(11):1749–1757, November 1988.

[16] D. T. Slock and T. Kailath, Fast transversal filters with data sequence weighting, *IEEE Trans. Acoust. Speech Signal Process.*, **37**(3):346–359, March 1989.

[17] R. Roy and T. Kailath, ESPRIT — Estimation of Signal Parameters via Rotational Invariance Techniques, *IEEE Trans. Acoust. Speech Signal Process.*, **37**(7):984–995, July 1989.

[18] B. Ottersten and T. Kailath, Direction-of-arrival estimation for wideband signals using the ESPRIT algorithm, *IEEE Trans. Acoust. Speech Signal Process.*, **38**(2):317–327, February 1990.

[19] D. T. Slock, L. Chisci, H. Lev-Ari, and T. Kailth, Modular and numerically stable multichannel statistical signal processing, *IETE Technical Rev.*, **35**(2):41–51, March-April 1990.

[20] R. Roy and T. Kailath, ESPRIT - Estimation of Signal Parameters via Rotational Invariance Techniques, *J. Optical Engrg.*, **29**(4):296–312, April 1990.

[21] J. M. Jover, T. Kailath, H. Lev-Ari, and S. K. Rao, On the analysis of synchronous computing systems, *SIAM J. Comput.*, **19**(4):627–643, August 1990.

[22] R. Roy, B. G. Sumpter, D. W. Noid, and B. Wunderlich, Estimation of dispersion relations from short-duration molecular dynamics simulations, *J. Phys. Chem.*, **94**(15):5720–5729, 1990.

[23] A. Swindlehurst and T. Kailath, On the Sensitivity of the ESPRIT Algorithm to Non-Identical Subarrays, *Sadhana J.*, **15**(3):197–212, Nov. 1990.

[24] D. Slock and T. Kailath, Numerically stable fast transversal filters for recursive least-squares adaptive filtering, *IEEE Trans. Signal Process.*, **39**(1):92–114, Jan 1991.

[25] M. Viberg and B. Ottersten , Sensor Array Processing Based on Subspace Fitting *IEEE Trans. Signal Process.*, **39**(5):1110–1121, May 1991.

[26] B. Ottersten, M. Viberg, and T. Kailath, Performance Analysis of the Total Least Squares ESPRIT Algorithm, *IEEE Trans. Signal Process.*, **39**(5):1122–1135, May 1991.

[27] M. Viberg, B. Ottersten, and T. Kailath, Detection and Estimation in Sensor Arrays Using Weighted Subspace Fitting, *IEEE Trans. Signal Process.*, **39**(11):2436–2449, Nov. 1991.

Papers Accepted by Refereed Journals.

[1] R. Roy, A. Paulraj and T. Kailath, Estimation of Signal Parameters via Rotational Invariance Techniques - ESPRIT, *J. Indian Inst. of Technology.*

[2] Y. Bresler, T. Kailath, and A. Macovski, Tracking of Shift and Shape Parameters, *IEEE Trans. Automat. Control.*

[3] M. Viberg, B. Ottersten, and T. Kailath, Subspace Based Detection for Linear Structural Relations, *J. Combin. Inform. System Sci.*, **16**(1&2).

[4] B. Ottersten and M. Viberg and T. Kailath, Analysis of Subspace Fitting and ML Techniques for Parameter Estimation from Sensor Array Data *IEEE Trans. on Signal Process.*, **40**(3), March 1992.

[5] D. T. M. Slock and T. Kailath, A modular multichannel multiexperiment fast transversal filter and a prewindowing framework for covariance RLS. *Signal Process.*

[6] A. Swindlehurst, B. Ottersten, R. Roy, and T. Kailath, Multiple Invariance ESPRIT, *IEEE Trans. on Signal Process.*, April, 1992.

[7] A. Swindlehurst and T. Kailath, A Performance Analysis of Subspace-Based Methods in the Presence of Model Errors – Part I: The MUSIC Algorithm, *IEEE Trans. on Signal Process.*, July, 1992.

[8] A. Swindlehurst and T. Kailath, Algorithms for Azimuth/Elevation Direction Finding Using Regular Array Geometries, *IEEE Trans. on AES.*

Papers Submitted to Refereed Journals.

[1] A. Swindlehurst and T. Kailath, A Performance Analysis of Subspace-Based Methods in the Presence of Model Errors, Pt. II: The MUSIC Algorithm, *IEEE Trans. Acoust. Speech Signal Process.*

[2] Marc Goldburg, Michael J. Genossar. and Thomas Kailath, Optimal coefficient selection for discrete time wavelet filters. *IEEE Trans. Acoust. Speech Signal Process.*, June 1991, under review.

Contributed Presentations at Technical Conferences

[1] A. Paulraj, R. Roy and T. Kailath, Estimation of Signal Parameters via Rotational Invariance Techniques - ESPRIT, *19th Asilomar Conference on Circuits, Systems and Computers*, pp. 83-89, Monterey, CA, November 6, 1985.

[2] D. Spielman, A. Paulraj and T. Kailath, A High Resolution Algorithm for Combined Time-of-Arrival and Direction-of-Arrival Estimation, *19th Asilomar Conference on Circuits, Systems and Computers*, pp. 90-93, Monterey, CA, November 6, 1985.

[3] D. Spielman, A. Paulraj and T. Kailath, Performance Analysis of the MUSIC Algorithm, *ICASSP*, pp. 1901-1912, Tokyo, Japan, April 1986.

[4] D. Spielman, A. Paulraj and T. Kailath, Eigenstructure Approach to Directions-of-Arrival Estimation in IR Detector Arrays, *ICASSP*, pp. 1833-1836, Tokyo, Japan, April 1986.

[5] F. McCarthy, A. Paulraj and T. Kailath, Eigenstructure Approach to Doppler Estimation for Wideband Signals, *ICASSP*, pp. 1917-1920, Tokyo, Japan, April 1986.

[6] R. Roy, A. Paulraj and T. Kailath, "Direction-of-Arrival Estimation by Subspace Rotation Methods - ESPRIT, *ICASSP*, pp. 2495-2498, Tokyo, Japan, April 1986.

[7] A. Paulraj, T. J. Shan, V. U. Reddy and T. Kailath, A Subspace Approach to Determine Sensor Gain and Phase with Applications to Array Processing, *SPIE's 30th Annual Tech. Symposium*, pp. 102-109, San Diego, CA, August 1986.

[8] R. Roy, A. Paulraj and T. Kailath, Estimation of Signal Parameters via Rotational Invariance Techniques - ESPRIT, *30th Annual Inter'l. SPIE Conference*, pp. 94-101, August 1986, San Diego, CA.

[9] A. Paulraj, R. Roy and T. Kailath, Estimation of Signal Parameters via Rotational Invariance Techniques - ESPRIT, 1986 IEEE Military Communications Conference, October 1986, Monterey, CA.

[10] V. U. Reddy, A. Paulraj, T. J. Shan and T. Kailath, Modified Capon's Beamformer for Coherent Interference, *Twentieth Annual Asilomar Conf. on Signals, Systems and Computers*, pp. 110-113, Pacific Grove, CA, November 1986

[11] R. Roy, A. Paulraj and T. Kailath. Comparative Performance of ESPRIT and MUSIC for Direction-of-Arrival Estimation. *Twentieth Annual Asilomar Conf. on Signals, Systems and Computers.* pp. 580-548, Pacific Grove, CA, November 1986

[12] R. Roy, A. Paulraj and T. Kailath, Estimation of Signal Parameters via Rotational Invariance Techniques - ESPRIT, Platinum Jubilee Conference on Systems and Signal Processing, pp. 207-214, Bangalore, India, December 1986.

[13] R. Roy, A. Paulraj, and T. Kailath, Comparative performance of ESPRIT and MUSIC for direction-of-arrival estimation, pages 2344–2347, Dallas, TX, April 1987. ICASSP-87.

[14] D. T. Slock, J. M. Cioffi, and T. Kailath, A fast transversal filter for adaptive line enhancing,, pages 419–422, Dallas, TX, April 1987. ICASSP-87.

[15] Y. Bresler, V. U. Reddy, and T. Kailath, A polynomial approach to optimum beamforming for correlated or coherent signal and interference, pages 2292–2295, Dallas, TX, April 1987. ICASSP-87.

[16] R. Roy, A. Paulraj, and T. Kailath, ESPRIT - a high resolution multiple signal direction finding technique. Arlington, VA, May 1987. 1987 SDI Tech. Achievements Symposium.

[17] P. Comon and T. Kailath, An array processing technique using the first principal component, Grenoble, France, September 21-23 1987. International Workshop on SVD and Signal Processing.

[18] R. Roy and T. Kailath, Total least-squares esprit, pages 297–301, Pacific Grove, CA, November 2-4 1987. 21st Asilomar Conference on Signals, Systems and Computers.

[19] B. Ottersten and T. Kailath, ESPRIT for wideband signals,, pages 98–102, Pacific Grove, CA, November 2-4 1987. 21st Asilomar Conference on Signals, Systems and Computers.

[20] V. U. Reddy, A. Paulraj, and T. Kailath, SINR performance of the minimum variance beamformer in the presence of correlated interference, India, December 1987. International Symposium on Electronic Devices, Circuits and Systems.

[21] R. Roy and T. Kailath, Total least squares ESPRIT for sensor array processing, pages 115–116, Bangalore, India, January 8-12 1988. Proc. INDO-US Workshop on Systems and Signal Processing.

[22] D. T. M. Slock and T. Kailath, Numerically stable fast recursive least-squares transversal fil ters, pages 1365–1368, New York, April 1988. Intern'l. Conference on Acoustics, Speech and Signal Processing.

[23] B. Ottersten and T. Kailath, Wideband direction-of-arrival estimation using the ESPRIT algorithm, pages 2666–2669, New York, April 1988. Intern'l. Conference on Acoustics, Speech and Signal Processing.

[24] A. L. Swindlehurst and T. Kailath, Passive direction-of-arrival and range estimation for near-field sources, pages 123–128, Minneapolis, MN, August 1988. 4th Spectral Estimation Workshop.

[25] R. Roy and T. Kailath, Invariance techniques and high resolution null steering,, pages 358–367, San Diego, CA, August 1988. 32th SPIE Symposium for Advanced Algorithms and Architectures for Signal Processing.

[26] A. L. Swindlehurst and T. Kailath, Near-field source parameter estimation using a spatial Wigner distribution approach, pages 86–92, San Diego, CA, August 1988. 32th SPIE Symposium for Advanced Algoriothms and Architectures for Signal Processing.

[27] R. Roy, B. Ottersten, L. Swindlehurst, and T. Kailath, Multiple invariance ESPRIT,, pages 583–587, Pacific Grove, CA, November 1988. 22st Asilomar Conference on Signals, Systems and Computers.

[28] A. L. Swindlehurst and T. Kailath, Detection and estimation using the third moment matrix,, pages 2325–2328, Glasgow, Scotland, May 23-26 1989. Proc. Intern'l. Conf. Acoustics, Speech and Signal Processing.

[29] D. Slock, L. Chisci, H. Lev-Ari, and T. Kailath, Modular and numerically stable multichannel FTF algorithms,, pages 1039–1041, Glasgow, Scotland, May 23-26 1989. Proc. Intern'l. Conf. Acoustics, Speech and Signal Processing.

[30] B. Ottersten, M. Viberg, and T. Kailath, Asymptotic analysis of the total least squares ESPRIT algorithm, pages 146–157, San Diego, August 1989. SPIE 33rd Annual Inter'l. Symp. on Optical and Optoelectronic Appl. Sci. and Engg.

[31] R. Roy, M. Goldburg, B. Ottersten, L. Swindelhurst, M. Viberg, and T. Kailath, ESPRIT and uniform linear arrays, pages 370–380, San Diego, August 1989. SPIE 33rd Annual Inter'l. Symp. on Optical and Optoelectronic Appl. Sci. and Engg.

[32] A. L. Swindlehurst, R. Roy, and T. Kailath, Suboptimal subspace-fitting methods for multidimensional signal parameter estimation., pages 197–208, San Diego, CA, August 1989. SPIE 33rd Annual Inter'l. Symp. on Optical and Optoelectronic Appl. Sci. and Engg.

[33] D. T. Slock and T. Kailath, Multichannel fast transversal filter algorithms for adaptive broadband beamforming,, pages 22–33, San Diego, CA, August 1989. SPIE 33rd Annual Inter'l. Symp. on Optical and Optoelectronic Appl. Sci. and Engg.

[34] B. Ottersten, T. Kailath, M. Viberg, and B. Wahlberg, Stochastic maximum likelihood estimation in sensor arrays by weighted subspace fitting, pages 599–603, Asilomar, CA, October 1989. 23rd Asilomar Conference on Circuits, Signals and Computers.

[35] M. Viberg, B. Ottersten, and T. Kailath, Direction-of-arrival estimation and detection using weighted subspace fitting, pages 604–608, Asilomar, CA, October 1989. 23rd Asilomar Conference on Circuits, Signals and Computers.

[36] B. Ottersten, R. Roy, and T. Kailath, Signal waveform estimation in sensor array processing,, pages 787–791, Asilomar, CA, October 1989. 23rd Asilomar Conference on Circuits, Signals and Computers.

[37] B. Ottersten, M. Viberg, and T. Kailath, Analysis of algorithms for sensor arrays with invariance structure, pages 2959–2962, Albuquerque, New Mexico, April 1990. Intern'l. Conf. Acoustics, Speech and Signal Processing.

[38] A. L. Swindlehurst and T. Kailath, An analysis of subspace fitting algorithms in the presence of sensor errors, pages 2647–2650, Albuquerque, New Mexico, April 1990. Intern'l. Conf. Acoustics, Speech and Signal Processing.

[39] B. Ottersten and M. Viberg, Asymptotic robustness of sensor array processing methods, pages 2635–2638, Albuquerque, New Mexico, April 1990. Intern'l. Conf. Acoustics, Speech and Signal Processing.

[40] M. Goldburg and R. Roy, Application of ESPRIT to parameter estimation from uniformly sampled data, Albuquerque, New Mexico, April 1990. Intern'l. Conf. Acoustics, Speech and Signal Processing.

Books (and Sections Thereof) Published.

[1] R. Roy and T. Kailath, ESPRIT – Estimation of Signal Parameters via Rotational Invariance Techniques, *Proc. International Workshop on SVD and Signal Processing*, Sept. 21-22, 1987, in *Singular Value Decomposition and Signal Processing*, Elsevier Science Pubs., 1988.